

Indirect Probes of Supersymmetry Breaking in Multi-Km³ Neutrino Telescopes

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Recently it has been shown [1] that fluorescence telescopes with a large field of view can indirectly probe the scale of supersymmetry breaking. Here we show that depending on their ability to fight a large background, multi-Km³ volume neutrino telescopes might independently probe a similar breaking scale region, which lies between $\sim 10^5$ and $\sim 5 \times 10^6$ GeV. The scenarios we consider have the gravitino as the lightest supersymmetric particle, and the next to lightest (NLSP) is a long lived slepton. Indirect probes complement a proposal [2] that demonstrates that 1 Km³ telescopes can directly probe this breaking scale. A high energy flux of neutrinos might interact in the Earth producing NLSPs which decay into taus. We estimate the rate of taus, taking into account the regeneration process, and the rate of secondary muons, which are produced in tau decays, in multi-km³ detectors.

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I. INTRODUCTION

Extensions of the standard model of particle physics (SM) are currently being probed at the Large Hadron Collider (LHC). At the same time, features of these extensions can be probed by non accelerator experiments. It has recently been shown [1] that the supersymmetry breaking scale (\sqrt{F}) can be probed indirectly by large fluorescence telescopes, such as the JEM-EUSO Observatory. This scale, as well as Universal Extra Dimensions scenarios [3], can also be directly probed by 1 Km³ volume neutrino telescopes [2, 4], such as IceCube. Here we show that depending on their ability to fight a large background, multi-Km³ volume neutrino telescopes might also indirectly probe the scale of supersymmetry breaking.

We investigate scenarios where supersymmetry (susy) is broken at $\sqrt{F} < 10^{10}$ GeV, and the lightest supersymmetric particle is the gravitino. In many of these scenarios, including Gauge Mediation Susy Breaking models [5], the NLSP is a right-handed stau, whose lifetime is [2]:

$$c\tau = \left(\frac{\sqrt{F}}{10^7 \text{ GeV}} \right)^4 \left(\frac{100 \text{ GeV}}{m_{\tilde{\tau}_R}} \right)^5 10 \text{ km}, \quad (1)$$

where $m_{\tilde{\tau}_R}$ is the stau mass. The NLSP range depends on \sqrt{F} , and for $\sqrt{F} \gtrsim 5 \times 10^6$, they travel a long way before decaying while for lower values they decay after a short travel. It has been shown [2, 4] that neutrino telescopes can directly probe this scale, probing scenarios where $5 \times 10^6 \lesssim \sqrt{F} \lesssim 5 \times 10^8$ GeV, while large fluorescence telescopes [1, 6], such as the JEM-EUSO Observatory [7], can probe scenarios where NLSPs decay and $\sqrt{F} \lesssim 5 \times 10^6$ GeV.

In this article we show that multi-Km³ volume neutrino telescopes can probe the same \sqrt{F} region as large fluorescence telescopes. NLSP decays will yield a few events per year in the projected KM3Net neutrino telescope [8], or in an expanded version of IceCube [9]. However, while fluorescence telescopes have a clean signature of these events, probes by neutrino telescopes will depend on the ability to discriminate taus (τ s) produced in NLSP decays from a large background.

A detectable rate of NLSPs in a 1 Km³ neutrino telescope, such as IceCube, can be produced by high energy neutrinos interactions in the Earth. Here we consider the same NLSP production mechanism, but analyze scenarios where these decay, probing a complementary breaking scale, where $\sqrt{F} \lesssim 5 \times 10^6$ GeV.

High energy τ s are produced in NLSP decays and undergo a regeneration process, where τ neutrinos (ν_τ) produced from τ decay, charge current interact in the Earth and produce a new τ . This process will expand the fraction of the Earth volume within which the τ can decay and still reach the detector. We also consider the flux of muons produced when these secondary τ s decay.

The caveat in probing \sqrt{F} [2] comes from the fact that NLSPs lose less energy and have a much larger range while transversing the Earth when compared to SM leptons. This larger range compensates its lower production cross section. Here, when NLSP decays are considered, an extra decaying volume is gained due to the τ regeneration process.

Multi-km³ neutrino telescopes proposals exist, either as a new telescope in the Mediterranean Sea [8] or as an expansion of IceCube [9]. Here we show that depending on their final design and their ability to fight a large background, they might be able to probe the \sqrt{F} region which allows NLSPs decays in the Earth.

In the next section we describe our simulation of NLSP production, propagation and energy loss, which reproduces the analysis described in [2, 4]. Follows the description of our simulation of NLSP decays with τ production; τ decay and regeneration process as well as muon pro-

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duction, which is the same used in [1]. The event rate in neutrino telescopes will depend on its design. In Section III we discuss this point, and determine the rates of these events in a 1 Km³ neutrino telescope. In section IV the rate is determined for multi-km³ telescopes. In Section IV A we analyze τ specific signatures, as well as a cosmological background. Finally we present our conclusions.

II. NLSP PRODUCTION

As shown in [2], NLSPs can be produced from the interaction of high energy neutrinos in the Earth. Although the production cross section related to this process is even lower than the one for SM leptons, the flux of NLSPs will still be considerable due to its much larger range, as described in the previous section.

Here we take the Waxman-Bahcall (WB) [10] upper limit on the neutrino flux hitting the Earth as a reference for our analysis. Our result is normalized by this upper limit, and can be translated to any other flux if properly rescaled. We consider neutrino production from optically thin sources, and the WB limit (for a maximized cosmological evolution of sources) is given by

$$\left(\frac{d\phi_\nu}{dE_\nu}\right)_{\text{WB}} = \frac{4 \times 10^{-8}}{E_\nu^2} \text{GeV cm}^{-2} \text{s}^{-1} \text{sr}^{-1}, \quad (2)$$

where E_ν is the neutrino energy. It is important to note that although this limit was set for muon and electron neutrinos, our analysis is independent of the initial neutrino flavor. Any flavor of the left-handed sleptons, produced from neutrino interactions, immediately decay producing a chain that will always end up with right-handed staus (the NLSPs). For this reason, neither the initial neutrino flavor nor cosmogenic mixing due to oscillations alter our results.

NLSPs will be produced by the interaction of cosmogenic neutrinos in the Earth and the production cross section is determined as in [4]. It follows the same pattern as for SM lepton production by charge current interactions, where now the up or down type quark is a squark (\tilde{q}) and the chargino is the mediator in the t-channel. We also account for the sub-dominant neutralino exchange. From this interaction a left-handed slepton (\tilde{l}_L) and a \tilde{q} are produced and promptly decay, always producing two NLSPs at the end of the decay chain. The production energy threshold depends on $m_{\tilde{q}}$ and $m_{\tilde{l}_L}$ and is $\sim 10^5$ GeV, and the NLSP initial energy is $\sim E_\nu/6$ [4]. These NLSPs are typically right handed staus ($\tilde{\tau}_R$) which travel in parallel through the Earth. We take the chargino mass as $m_{\tilde{w}} = 250$ GeV, and $m_{\tilde{l}_L} = 150$ GeV, $m_{\tilde{\tau}_R} = 250$ GeV for the left-handed stau and the NLSP respectively, and consider three possibilities for the squark mass, $m_{\tilde{q}} = 300, 600$ or 900 GeV. There are constraints to the $\tilde{\tau}_R$ from big-bang nucleosynthesis [11].

NLSP production depends on the probability that neutrinos will interact in the Earth, and we use the Earth

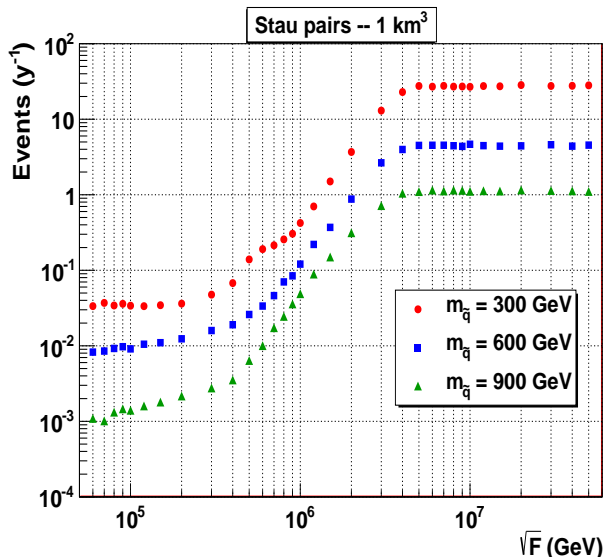


FIG. 1. Number of NLSP events per year in a km³ neutrino telescope versus the scale of susy breaking \sqrt{F} . It is assumed an initial neutrino flux equivalent to the WB limit. The curves are shown for different $m_{\tilde{q}}$ values.

density profile model described in [12, 13]. Our simulation of NLSP propagation includes its energy loss, due both to ionization and radiative processes. It follows the analysis described in [4, 14], where it is shown that the NLSP energy degradation due to radiative losses is suppressed when compared to SM leptons.

We check our NLSP production and propagation simulation by reproducing the direct detection rate and the energy distribution shown in [2, 4].

III. NLSP DECAY AND EVENT RATES IN 1 KM³ NEUTRINO TELESCOPES

Here we consider scenarios where \sqrt{F} is such that NLSPs decay after a short travel through the Earth. This distance equals $\gamma c\tau$, and can be determined from Equation 1. They decay into a τ and a gravitino, where the τ is much heavier than the gravitino. Figure 1 shows the number of NLSPs per year in a km³ neutrino telescope (positioned ~ 2 Km deep in the Earth) versus \sqrt{F} , and it is clear that NLSPs decay for $\sqrt{F} \lesssim 5 \times 10^6$ GeV.

In our Monte Carlo simulation $\mathcal{O}(10^5)$ neutrinos isotropically distributed reach the Earth. These are generated with energies between 10^5 to 10^{12} GeV, and are normalized by the WB limit. NLSPs are then produced according to the neutrino interaction probability distribution, which depends on the Earth density profile and the NLSP production cross section, and propagated, taking into account their energy loss, as described in the previous section. The neutrino interaction probability is convoluted by its survival probability to account for SM lepton production.

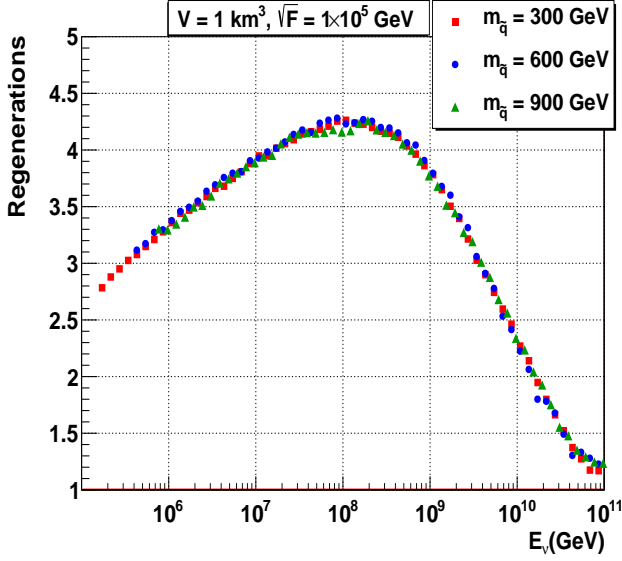


FIG. 2. Average number of τ regenerations. Only the τ s which reach a 1 km^3 detector are taken into account. Results are shown for three values of $m_{\tilde{q}}$, and as expected show no dependency on this parameter.

Once the NLSP production and propagation is simulated, NLSPs are randomly selected to decay according to their decay probability distribution, $P_d = 1 - \exp(-mx/E_{\tilde{\tau}_L} c\tau)$. The decay generate τ s isotropically distributed in the center of mass frame, which are boosted to the laboratory frame, mainly following the same direction as the NLSPs. τ s will then decay and generate ν_τ s and a regeneration process might take place. In 18% of the τ decay, a muon will be produced and, if close enough to the detector, its propagation will also be simulated.

The regeneration process depends on the τ energy. The fraction of energy carried by the ν_τ is determined as described in [15, 16]. The average number of regenerations are shown in Figure 2 as a function of the neutrino energy E_ν , for τ s that reach a 1 Km^3 detector positioned as IceCube.

We note that two NLSPs are always produced from the neutrino interaction in the Earth. These NLSPs will decay at different points in the Earth and the generated τ s will not follow the same coincidence pattern in the detector as the NLSPs.

In order to understand the possibility of NLSP indirect detection by neutrino telescopes, the detector shape is relevant. The τ average path and number of regenerations depend strongly on its energy. Up to 10^6 GeV the average path length is much smaller than a Km, but larger energies imply that this distance might be longer than the detector size. Events arriving horizontally with respect to the detector can go through fewer regeneration processes than the ones coming from below. Therefore, it is important to determine the event rate as a function of the detector volume as well as to take into account the

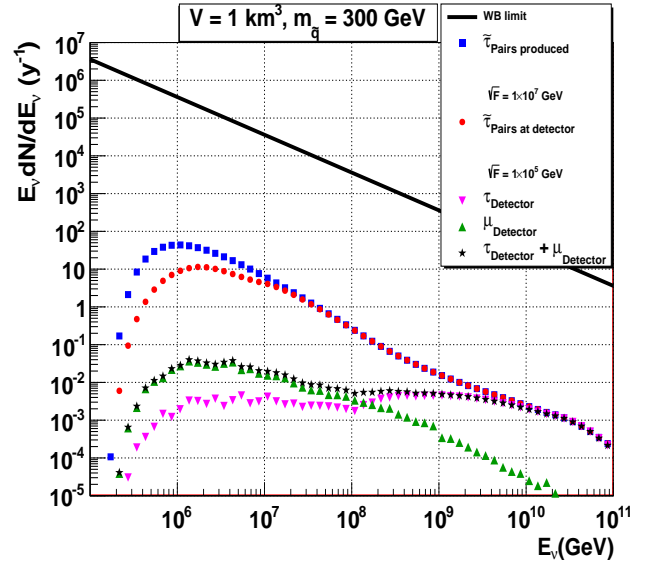


FIG. 3. Energy distribution of produced $\tilde{\tau}$ pairs (blue square), the fraction of these that reach the detector (red dots) assuming $\sqrt{F} = 10^7 \text{ GeV}$ and of τ s (pink triangles) and μ s (green triangles) as well as their sum (black stars) that reach the detector assuming $\sqrt{F} = 10^5 \text{ GeV}$. Here we take $m_{\tilde{q}} = 300 \text{ GeV}$. The distributions for $m_{\tilde{q}} = 600$ and 900 GeV , are very similar in shape with lower number of events.

detector shape. One important point is that due to the regeneration process, the effective volume for NLSP production will be enhanced when compared to direct NLSP detection.

We consider a 1 km^3 cylindrical detector, with a 0.564 Km radius, 1 Km height, and buried 2 Km deep in the Earth. Our results are therefore relevant both for IceCube [9] and Km3Net [8] neutrino telescopes. We show our results as a function of two arbitrary values of \sqrt{F} , 10^5 and 10^7 GeV , where the lower value represents the maximum NLSP decay rate and the upper one the region where NLSPs are stable while transversing the Earth.

Figure 3 shows the energy distribution for events reaching a 1 Km^3 detector. Up to neutrino energies of 10^7 GeV the τ rate is smaller than the μ one and this relation inverts at $\sim 10^8 \text{ GeV}$. At lower energies the τ decays almost instantly, which lower it's detection probability when compared to larger energies where it travels for a while before decaying. For $E_\nu \geq 5 \times 10^9 \text{ GeV}$ all τ s will reach the detector. This figure assumes $m_{\tilde{q}} = 300 \text{ GeV}$, whereas the distributions for $m_{\tilde{q}} = 600$ and 900 GeV , are very similar in shape with lower number of events. The total rate of events in a Km^3 detector per year, for the three values of $m_{\tilde{q}}$, are shown in Table I. It is important to note that the number of events in larger detectors will not necessarily scale linearly with these results, as we will show below, due to the importance of the shape of the detector.

The τ and μ energy at the detector is shown in Figure 4. It can be seen that most τ s that reach the detector

$m_{\tilde{q}}$ (GeV)	V (km ³)	$\tilde{\tau}$ (y ⁻¹)	τ (y ⁻¹)	μ (y ⁻¹)	$\mu + \tau$ (y ⁻¹)
300	1	27.7	0.07	0.21	0.28
300	21	521.5	1.60	2.36	3.95
300	65	1450.5	4.41	5.85	10.26
600	1	4.5	0.02	0.04	0.06
600	21	100.6	0.51	0.47	0.98
600	65	260.0	1.47	1.27	2.74
900	1	1.1	0.01	0.01	0.02
900	21	28.2	0.22	0.15	0.37
900	65	73.0	0.65	0.41	1.05

TABLE I. $\tilde{\tau}$ pair, τ and μ rates per year in a Km³ neutrino telescope at ~ 2 Km deep, for neutrino telescopes of 1, 21 and 65 Km³ volumes. Results are given for 3 $m_{\tilde{q}}$, assuming $\sqrt{F} = 10^7(10^5)$ GeV for $\tilde{\tau}$ pairs (τ s and μ s).

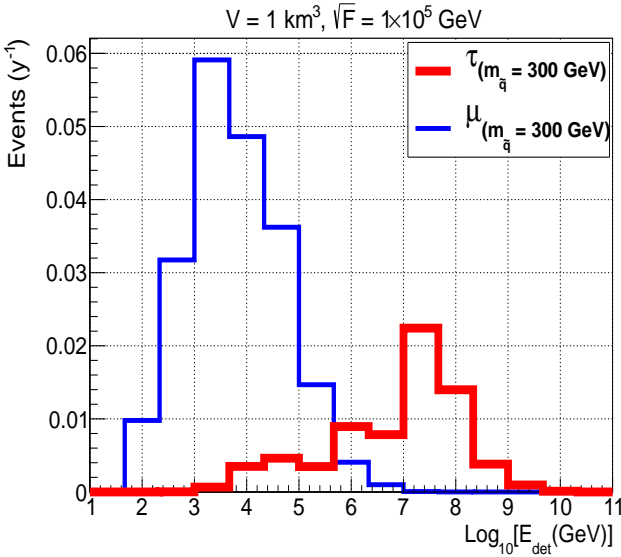


FIG. 4. Distribution of τ and μ energy at a 1 Km³ detector for $\sqrt{F} = 10^5$ GeV. Results are shown for $m_{\tilde{q}} = 300$ GeV. Other values of $m_{\tilde{q}}$ s have similar distributions with less events.

have larger energies than the μ s, reflecting the distribution in Figure 3.

IV. DECAY RATES IN MULTI-KM³ TELESCOPES

As can be seen in Table I, the indirect probe of the susy breaking scale is not promising at 1 Km³ neutrino telescopes. However there are studies [9] and proposals [8] of multi-Km³ detectors. Here we determine the τ and μ rates from NLSP decays in these detectors and analyze how well they can probe this scale.

We take a 2 and 4 Km radius extension to our current cylindrical configuration (as proposed in [9] for an Ice-Cube extension) as our case scenarios. This leads to 21 and 65 Km³ volumes. It is important to note that due

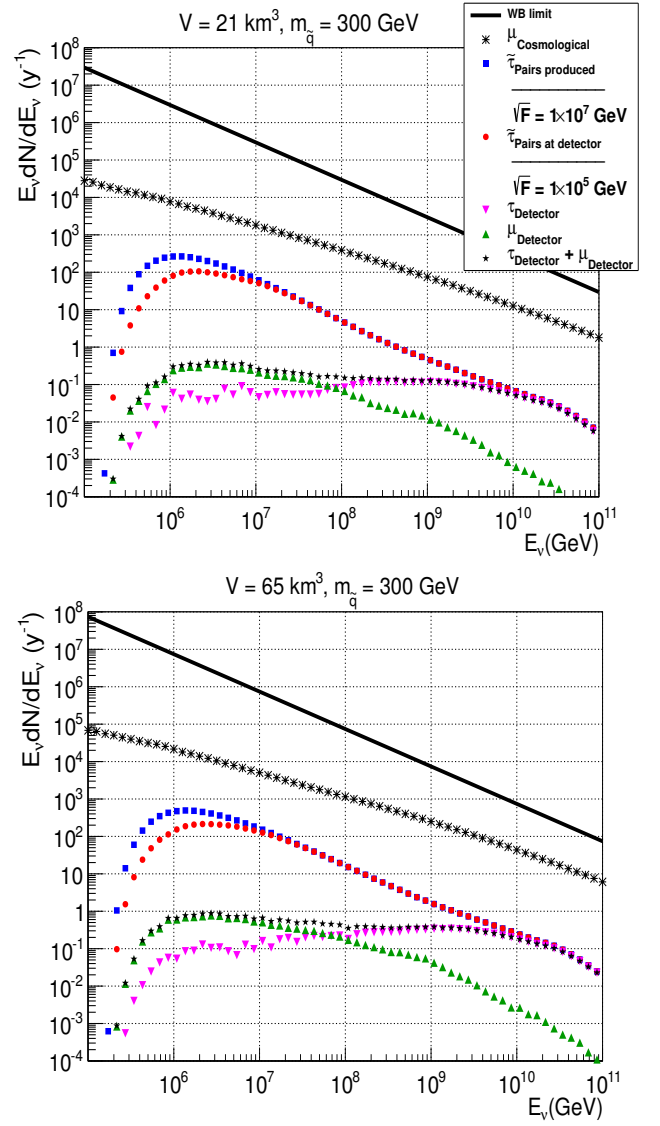


FIG. 5. Same as Figure 3, but now for extended neutrino telescopes. Top plot shows results for 21 Km³ and bottom for 65 Km³ volume telescopes. Both show results for $m_{\tilde{q}} = 300$ GeV. It also shows the cosmological muon background (black * line) energy distribution.

to the regeneration process, the increase in the indirect detection rate will depend on the shape of the extended detector.

In Figure 5 we show the τ and μ rates in such telescopes, where we assume $\sqrt{F} = 10^5$ GeV, representing scenarios where all NLSPs decay. The event rate per year for these extended volumes are shown in Table I. The distribution for the τ and μ arrival energy at the detector for these events are very similar to the ones shown in Figure 4.

As shown in Table I the τ and μ rates in extended neutrino telescopes are significant, with a few events per year for $m_{\tilde{q}} = 300$ GeV and 1 event per year in the

larger volume for $m_{\tilde{q}} = 900$ GeV. These rates are at the same level as NLSP direct detection [2, 4] and indirect dark matter detection [17] in 1 Km^3 neutrino telescopes. Therefore one needs to determine possible backgrounds for these events.

A. Backgrounds in Multi-Km³ Telescopes

Under the scenarios we are considering, while NLSP direct detection has a clean and very distinctive signature, with two NLSPs transversing the detector simultaneously, NLSP indirect detection has a considerable background. It comes both from atmospheric as well as from cosmological neutrinos, where the latter is also the source of NLSPs. In the indirect case, each produced NLSP will decay at different times and therefore almost all τ s and μ s will transverse the detector as a single event.

The number of events in detectors of different volumes is shown in Table I. Figure 5 shows the energy distribution of cosmological μ s per year in both 21 and 65 Km³ telescopes. Muons from atmospheric neutrinos have lower energy compared to the cosmological neutrinos and can be significantly reduced. However cosmological neutrinos will yield an almost unreducible background. The only way to distinguish μ s coming from NLSP decays, would be through a time correlation with the NLSP produced τ s.

However there is also a small but significant number of τ s for extended telescopes. In the best case scenario, four taus per year can be seen in the 65 Km³ volume telescope. There are many techniques to distinguish τ s from μ s in neutrino telescopes, as described in the next section. Most of these signatures are favored by an increased telescope size. As an example, in the case of the double-bang [18] signature, two cascades can occur inside the detector. For a 1 km^3 telescope there is a tight τ energy window, in order to contain these cascades, while a larger detector has a much larger efficiency for this signature. There is an ongoing effort to improve discrimination between μ s and τ s in neutrino telescopes [19]. Once this discrimination is done efficiently, the background for τ s generated by NLSP decays will depend on neutrino oscillations. If one assumes that cosmological neutrinos oscillates, always arriving in a $1 : 1 : 1$ ratio of ν_e, ν_μ and ν_τ s, there will also exist an almost irreducible τ background (see next section). In this case, μ s and τ s produced by NLSP decays have to be time correlated in order to reduce the background. Otherwise, NLSP produced τ s will be background free.

V. τ SIGNATURES IN NEUTRINO TELESCOPES

In order to check our regeneration simulation, we generated τ s from a distribution of $10^6 \nu_\tau$ s isotropically hitting the Earth. The regeneration process was then sim-

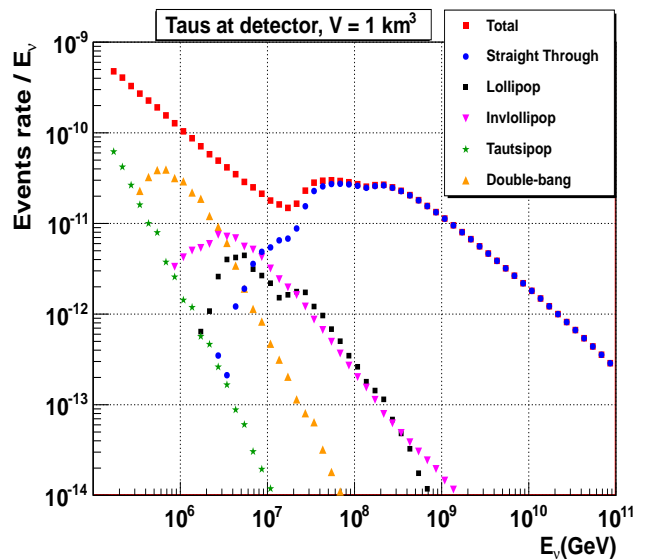


FIG. 6. Fraction of generated events which produce a specific τ signature as labeled. In red is shown the total number of τ s that reach the detector. A 1 Km^3 volume is assumed.

ulated as described in Section III. We analyzed the following τ signatures [18, 20]: double bang, where the ν_τ charge current interacts in the detector producing a τ plus a hadronic shower and the produced τ subsequently decays producing a second shower; lollipop, where a τ enters the detector and decays inside it producing one shower; inverted lollipop, where one shower is produced together with a τ which in its turn goes through the detector, and finally the tautsipop signature, where as in the double bang, two showers are produced but too close to each other looking like a single shower.

Figure 6 shows the fraction of generated events corresponding to each τ signature assuming a 1 km^3 volume, and the number of τ s that go straight through the detector. Table II shows the fraction of events for each specific signature, integrated in energy and the number of events assuming that $1/3$ of the WB upper limit corresponds to ν_τ s. Both cases integrates the energy above 2×10^6 GeV, corresponding to the minimal energy with which most τ s arrive at the detector (see Figure 4). These results are consistent with [21].

Table II shows that if $1/3$ of the cosmological neutrino flux arrives at the Earth as ν_τ , there will also be a significant cosmological background for the NLSP generated τ s. The only chance for extended neutrino telescopes to probe decaying NLSPs will therefore be a time correlation between both τ s or a τ and a μ produced from NLSP decay.

VI. CONCLUSIONS

We have shown that multi-Km³ neutrino telescopes are potentially sensitive to indirectly probe the scale of

TABLE II. Fraction of generated events with specific τ signature (see text), for 1, 21 and 65 Km^3 neutrino telescopes; and integrated number of events assuming an initial ν_τ flux equivalent to 1/3 of the WB limit. Only events with energies above 2×10^6 were accepted, since most NLSP produced τ s arrive the detector with energies above this value.

V = 1 km^3						
Limit	Total	Lollipop	Inv Lollipop	Tautsipop	Straight Through	Double Bang
$f_N(10^{-10})$	7.9	0.37	0.56	0.009	4.9	0.3
WB	31	1.5	2.2	0.037	19.5	1.3
V = 21 km^3						
$f_N(10^{-10})$	270	29	36	0.3	120	40
WB	1052	114	143	1.3	457	158
V = 65 km^3						
$f_N(10^{-10})$	860	83	130	1.2	300	200
WB	3420	328	517	4.7	1180	790

susy breaking. However although a significant number

of NLSP generated τ s will trigger these telescopes, this probe depends on the ability to distinguish these τ s from a large background. This background is composed of τ s produced by cosmological neutrinos, that will be significant if one assumes an equal neutrino flavor ratio at the Earth, due to oscillations. If for any reason oscillations do not produce tau neutrinos, extended neutrino telescopes are able to probe the susy breaking scale in the range $10^5 \lesssim \sqrt{F} \lesssim 10^6$ GeV. Large fluorescence telescopes can also indirectly probe [1] the same \sqrt{F} range but with the advantage of a background free signature. Both these proposed indirect measurements complement direct susy breaking probes that can be done by 1 Km^3 neutrino telescopes [2, 4].

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